MAPPING HYDRAULICALLY PERMEABLE FRACTURES USING DIRECTIONAL BOREHOLE RADAR AND HOLE-TO-HOLE TOMOGRAPHY WITH A SALINE TRACER

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ABSTRACT

Reflection-mode borehole radar and transmission-mode radar tomograms image heterogeneity in the electromagnetic properties of rock. Heterogeneity may be produced by interfaces between different rock types, foliation, and fracturing. In crystalline rock, hydraulic flow is primarily through fracture networks rather than through the rock matrix. Borehole radar methods have been applied to help map flow paths in crystalline rock. Correlation of features identified in borehole radar reflection records and tomograms with hydraulic flow paths is generally uncertain because the records show responses to heterogeneity of all kinds, not just to hydraulically permeable fractures. Even in lithologically uniform rock, it is often not possible to distinguish fractures of high hydraulic permeabilities from those with low permeabilities.

It is possible to "erase" signatures from lithologic interfaces and rock fabric to identify the signatures of hydraulically permeable fractures by using a saline tracer in fractured crystalline rock because the electrical properties of the rock, except for the fractures that are open to infiltration by the brine solution, remain the same after the injection of the brine and may be removed by examining differences. Saline tracer experiments were carried out in 1995, 1996, and 1997 in the FSE well field at the Mirror Lake fractured-rock hydrology research site in Grafton County, New Hampshire. Comparisons of results from directional radar reflection surveys to well-to-well difference attenuation tomography in the same pairs of wells show generally good correspondence between the location of radar reflections and attenuation anomalies. Our results demonstrate the advantage of using a saline tracer for before-and-after difference mapping of hydraulically permeable fractures in lithologically heterogeneous rock and the utility of the coordinated use of directional borehole radar and hole-to-hole radar tomography.

INTRODUCTION

The U.S. Geological Survey Toxic Substances Hydrology Program has been conducting hydrologic, geologic, and geophysical studies at the Mirror Lake, Grafton County, New Hampshire fractured-rock hydrology research site (Fig. 1). A major objective of the Mirror Lake research is to develop better three-dimensional hydraulic flow models in fractured rock. As tools to aid in that objective, many surface and borehole geophysical techniques have been tested. Directional reflection mode radar and borehole-to-borehole radar tomography are among the tools that have proven to be useful. The lithology of much of the site is heterogeneous, however, and radar reflections and tomograms image that heterogeneity. The heterogeneous features, unfortunately, are not reliable indicators of hydraulic permeability, so that the response to the heterogeneity may actually detract from the ability of radar and tomography to delineate hydraulic flow paths. Even where tomograms and radar reflections do image water in a given fractured region of rock, it is not clear whether this water is hydraulically connected to other fractures. One way to address this question is by using a saline tracer that modifies the electrical conductivity of the water. By conducting radar reflection and hole-to-hole tomography surveys before and after brine injection it is possible to image the regions that have been changed because they have accepted the brine. In an earlier paper (Wright and others, 1996) we gave some results of before-and-after difference tomography between wells FSE-2 and FSE-3. Differences were observed in both radar reflections and in the tomograms.

A concern, however, was that with open wells some of the brine might have entered one or both of the

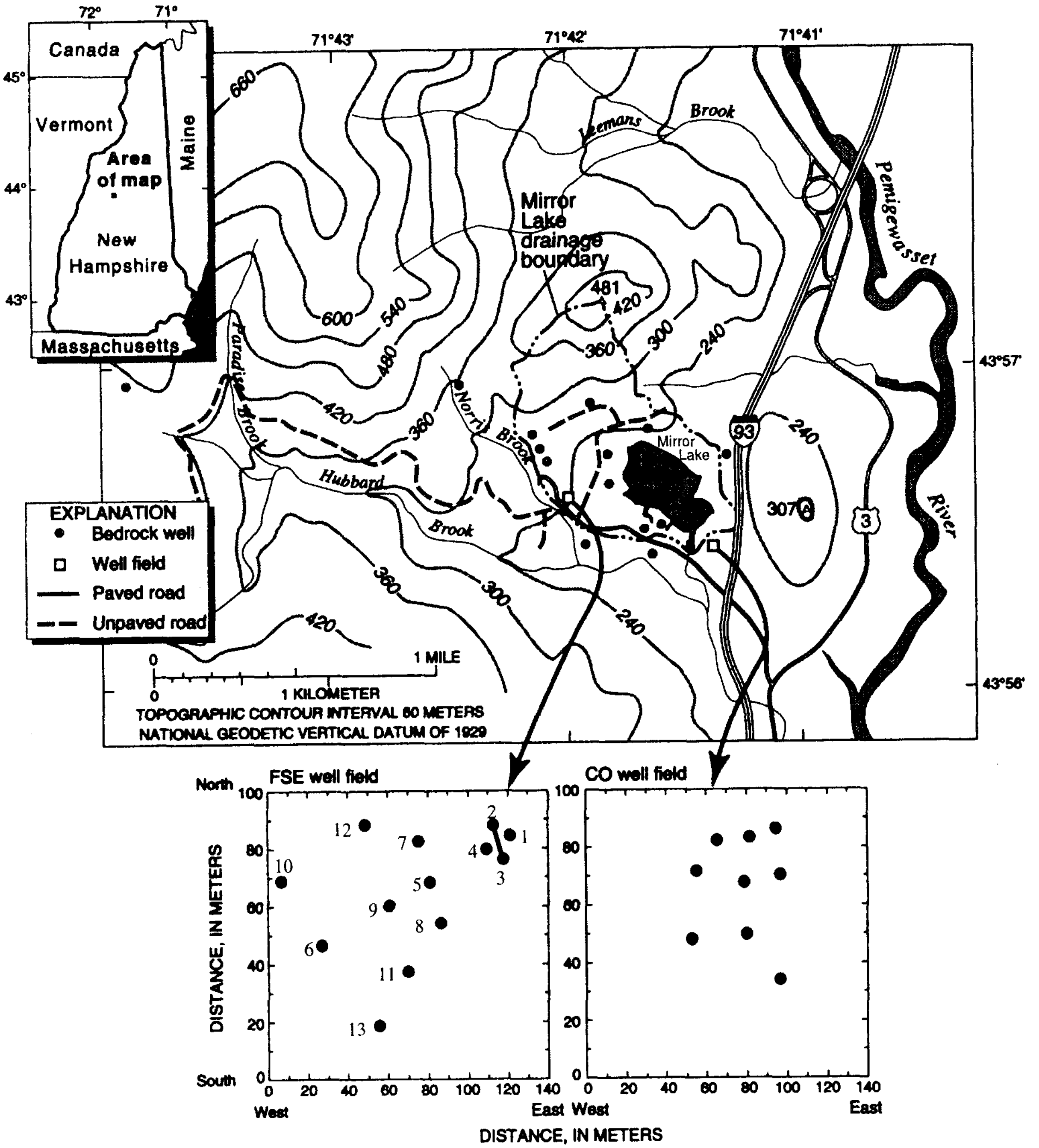
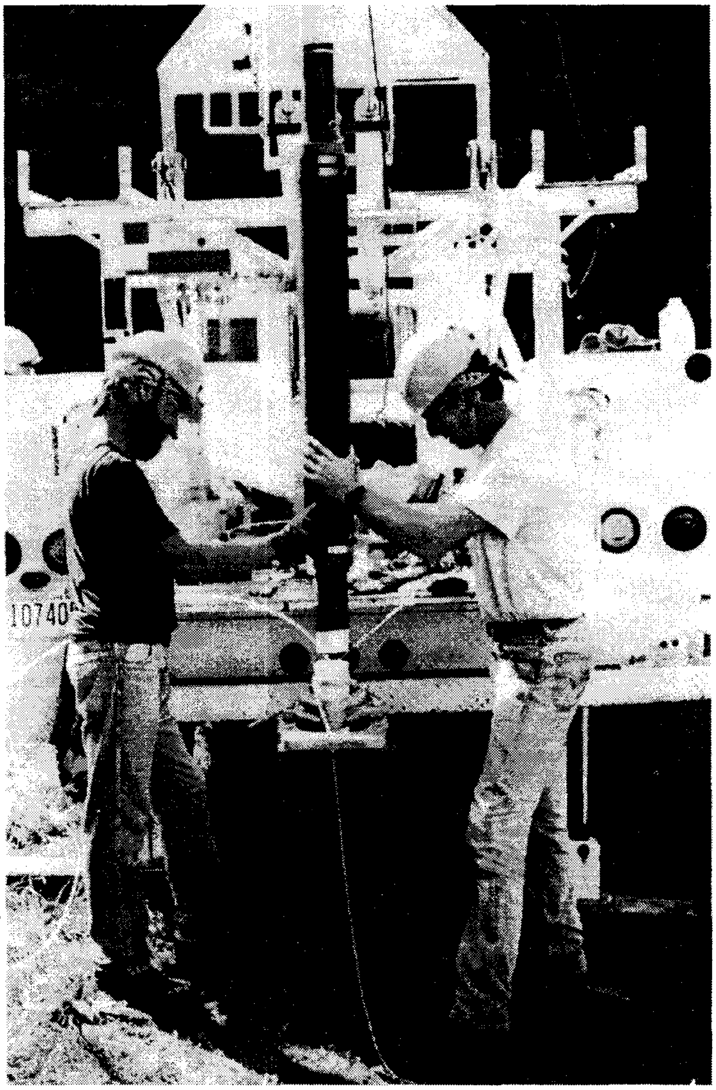


Figure 1. The Mirror Lake fractured-rock hydrology research site is located in Grafton County, New Hampshire. The work reported here is based on data obtained in and between wells FSE-2 and FSE-3, shown in the lower left inset.

observation wells and changed the electrical conductivity of the borehole fluid. A result would be a change in the loading of the radar antennas by the borehole fluid. Changes in antenna loading, in turn, could affect difference attenuation tomograms as well as returns from fractures observed using reflection mode radar. Analysis of data and tomography results obtained in 1996 suggests that this may, indeed, have happened. Therefore, in 1997, special packers were developed and installed in the observation wells to prevent brine from entering the observation wells. The tomography results suggest that the packers were effective. Fluid resistivity logs show some changes over the duration of the experiment, but we think this is the result of mixing caused by the movement of borehole tools in the wells and not due to the entry of brine into the observation wells.

LOG-THROUGH PACKERS



In order to prevent brine from entering the observation wells, log-through packers were developed and installed in wells FSE-1, FSE-2, and FSE-3. Figure 2 shows one of these packers being installed. Each rubber inflatable packer is 1 m long and is installed over a 726 mm (2.86") inside diameter polyvinylchloride (PVC) plastic pipe. Thus the center of the packer is open and radar, induction, and fluid resistivity borehole tools may be logged through the packers. Care was taken to minimize metal, but circular metal clamps at the top and bottom of each packer, visible in the figure, and small eye-bolts were necessary. It was judged that small pieces of metal with short vertical dimensions should have little effect on the radar antennas and that whatever effect they did have would be removed by the differencing employed in the tomographic processing. Prior knowledge of the locations of the most permeable zones in each of the wells allowed positioning of the packers at the proper depths to seal those zones from the wells and prevent brine entry.

Figure 2. One of the log-through packers being installed. The inflatable rubber bladder is 1 m long and is installed over a plastic pipe to allow borehole tools to be operated through the packer. Metal was minimized, but two metal clamps, similar to automotive radiator hose clamps, are located near each end, and small metal eye-bolts are located at the top of the packer section. Tubing for compressed air is also visible. (Photograph courtesy of Peter Joesten, USGS)

TRANSIENT HYDRAULIC RESPONSE

Transient hydraulic behavior in a fracture system is of great interest for hydraulic flow and transport studies, and the fact that we can observe transient hydraulic behavior in rock between wells by using saline tracers adds to the arsenal of techniques that can be used in studies of hydraulic flow and transport (Lane, 1996; Lane and others, 1996; Lane and others, 1998a; Lane and others, 1998b). Borehole radar and time-lapse difference tomography are being used to constrain numerical models of fluid-flow (Day-Lewis and others, 1997).

Amplitude versus depth logs of borehole-to-borehole radar signals from sequential "level runs" as brine was injected show that different permeable regions received the brine at different times and to different degrees. In this experiment the transient response of brine transport through permeable fractures penetrating the FSE-2 and FSE-3 plane was observed by conducting a series of "level runs" before and through the initial stages of brine injection into FSE-1, once during acquisition of the tomography data, and once at the conclusion of acquisition. A hole-to-hole "level run" denotes a run in which the transmitter and receiver are at the same depths in their respective wells and are moved in tandem. In our case our "level" runs actually had a small constant offset because the antenna in the receiver was about 1.7 m below the antenna in the transmitter due to different locations of the battery packs in the two tools. No compensating offset was used. Radar signal amplitude versus depth at six different times is shown in the top panel of Figure 3. The bottom panel of Figure 3 shows the conductivity of the fluid recovered at the pump in well FSE-4. Zero time is the time at which the brine injection began in FSE-1. About 20 minutes elapsed before the brine tracer began to be detected in FSE-4. There was then an almost linear rise in conductivity until about 65 minutes at which time a plateau was reached. At about 93 minutes, marked with a triangle symbol, we began taking tomographic data because it appeared that a quasi-steady state had been achieved. Tomography data acquisition continued until about 250 minutes (marked with a diamond symbol). The conductivity began a secondary rise at about the time we began taking data, peaked, and then dropped back slightly during our data acquisition. Injection and pumping rates and injected brine conductivities were held constant over this time. The vertical lines (solid, dotted, etc.) show the times at which the level runs shown on the top panel were run. The line types correspond in the top and bottom panels. The times noted for each level run are the times of initiation of the run. The early time level runs were conducted from depths of -20 m to -55 m and each run required about 6 minutes to complete.

In the top panel of Figure 3, a decrease in amplitude with time is observed from -42 to -46 m that correlates with the increase in fluid conductivity at the pumped well (FSE-4). Not all portions of this interval decrease at the same time. For example, the top portion responds later than the bottom portion which may indicate the direction of transport along fractures in this zone. The interval from -48.5 m to -54 m shows an increase in amplitude with time, as does the interval from -37 to -39 m. The interval from -26 m to -30.5 m showed little response through 76 minutes, but by the next level run at 122 minutes, there had been a substantial decrease in the amplitude in that interval. This was about 29 minutes after we had begun taking our data and changes in that region may have been missed in some of our tomography data. Perhaps the movement of tracer along a lower permeability fracture in this region is related to the slow secondary increase in the fluid conductivity that began at about 90 minutes. The reason or reasons why some regions show increases in amplitude while others show the expected decreases are not completely clear. One hypothesis is that some wave-guiding may have occurred between parallel fractures and the wave-guiding was stronger when the fractures were filled with brine than when they were filled with fresh water.

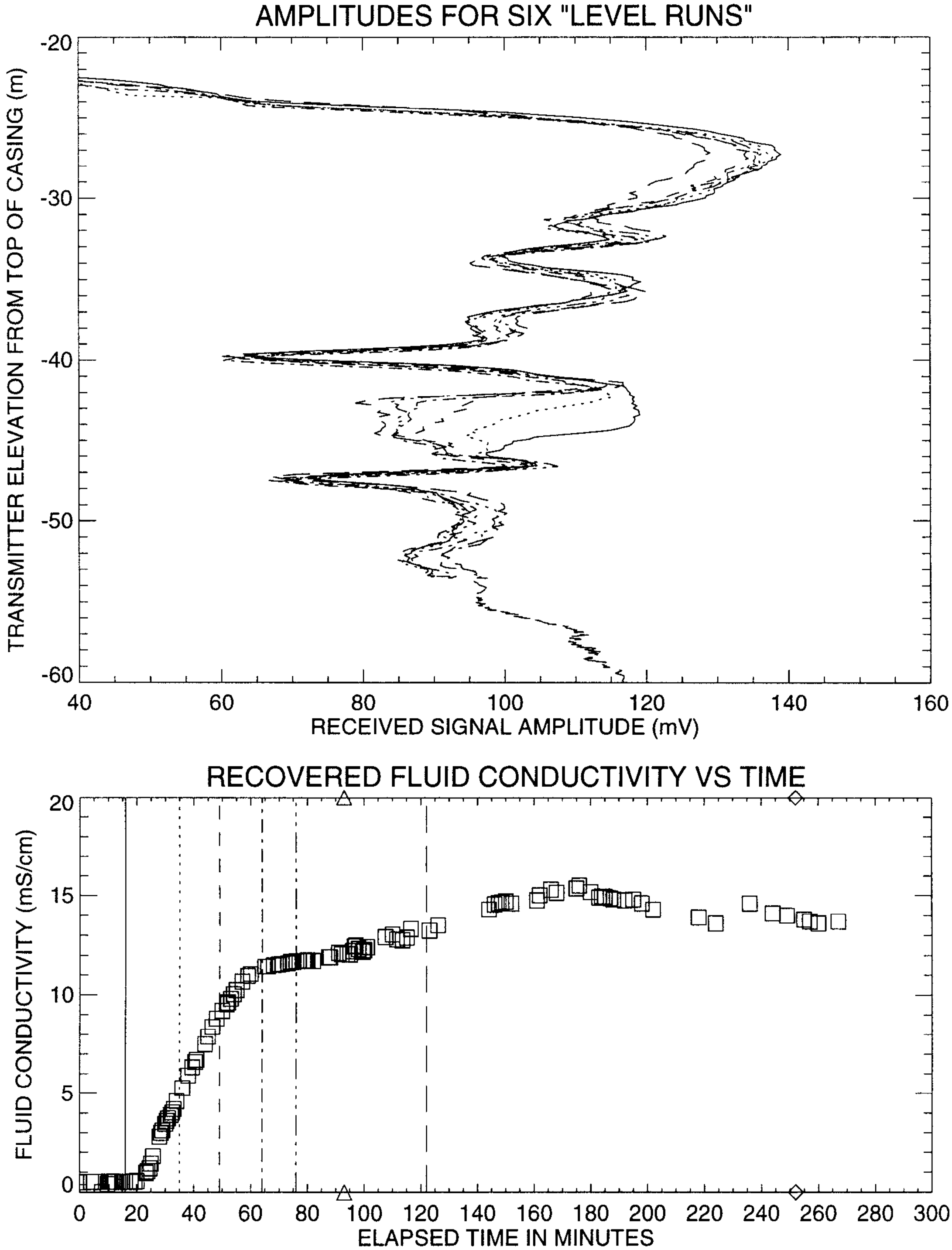


Figure 3. The effect of fluid conductivity on radar signal amplitudes. The upper panel shows well-to-well radar signal amplitude versus depth for six runs done at different stages of brine injection. The line types (solid, dotted, short dashed, etc.) correspond to the times shown on the bottom panel. The bottom panel also shows the conductivity of the fluid recovered at the pump in FSE-4 as a function of time relative to the initiation of brine injection. The triangle and diamond symbols on the time axis indicate beginning and ending of tomography data acquisition. The radar signal amplitudes vary with conductivity and the response differs at different depths.

ATTENUATION DIFFERENCE TOMOGRAM, RADAR REFLECTORS, AND INDUCTION LOGS

The tomogram shown in Figure 4 was derived from the data collected in 1997 with the USGS-built radar system. Radar and additional tomography has also been done with the MALA GeoScience RAMAC[1] borehole radar system (Lane and others 1996, Lane and others 1998b). The methods of processing were essentially the same as those used in 1995 (Wright and others, 1996). An interesting alternative computational approach using shifts in the frequency centroid has been developed (Liu and others, 1997).

In 1997 the USGS-built system had available transmitters designed for 60 MHz and 30 MHz center frequencies in granite. In 1995 and 1996 the 60 MHz transmitter was used, but in 1997 we used the 30 MHz transmitter because the 60 MHz transmitter would not fit into the PVC pipe. In addition to the use of packers and the lower frequency transmitter, injection and pumping procedures were different from those employed in 1995 and 1996. In 1995 brine was injected into FSE-1 while FSE-4 was pumped until a quasi-steady state was achieved. Then the injection and pumping were suspended for the duration of data acquisition. In 1995 we waited for over an hour to begin acquiring the tomography data because we were doing radar in one of the wells. In 1996, we commenced data acquisition immediately upon suspension of injection and pumping, but found major shifts in amplitudes, even in amplitude ratios, over the 2 to 3 hour period required for data acquisition. In particular, the 1996 data showed that conductivities in some regions were relaxing toward pre-injection levels during data acquisition. A consequence was strong artifacts induced in the difference tomograms. In 1997 we decided to commence data acquisition after achievement of quasi-steady state, as before, but to continue injection and pumping through the period of data acquisition to prevent any diminution of the brine conductivity during data acquisition.

The tomogram is displayed as a gray scale. The darker the gray the greater the change, either positive or negative, in calculated attenuation between post- and pre-injection conditions. The strongest change is observed at a depth of about -42 m adjacent to well FSE-2. This is hydraulically reasonable and confirms that the dominant flow path between wells FSE-1 and FSE-4 leaves the plane of those wells. The next largest change is centered at a depth of about -35 m adjacent to well FSE-3, and the top from -20 to -24 m also shows significant change.

Superimposed on the tomogram are traces of intersections of hydraulically permeable fractures. The trace orientations indicate how a particular fracture with its individual strike and dip intersects the FSE2-3 plane. The lengths of the traces are not significant, but the thicker traces adjacent to FSE-2 indicate those fractures interpreted to have high transmissivity (Lane, 1996).

Flanking the tomogram and superimposed fracture traces are electromagnetic induction logs run with a Century 9510 probe. The effect of borehole fluid conductivity for this probe is negligible in wells with a diameter of less than 10 cm (Williams, 1994), but FSE-2 and FSE-3 are approximately 15 cm in diameter and the probe may be showing some reaction to the borehole fluid conductivity. The measured conductivity below about -65 m is higher in FSE-2 than that in FSE-3 and may partially reflect the borehole fluid conductivity (Figure 5). The off-scale regions in both induction logs indicate the locations of the packers and are caused specifically by the metal rings near the top and bottom of each packer (Figure 2). The induction tool is responding mainly to the conductivity in the rock and several sharp increases in conductivity may indicate fractures. We have examined some of the other induction logs run at different times in the same wells and have not found large differences between them.

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[1]Use of equipment manufacturer and trade or model names is for identification purposes only and does not constitute an endorsement by the U.S. Geological Survey.

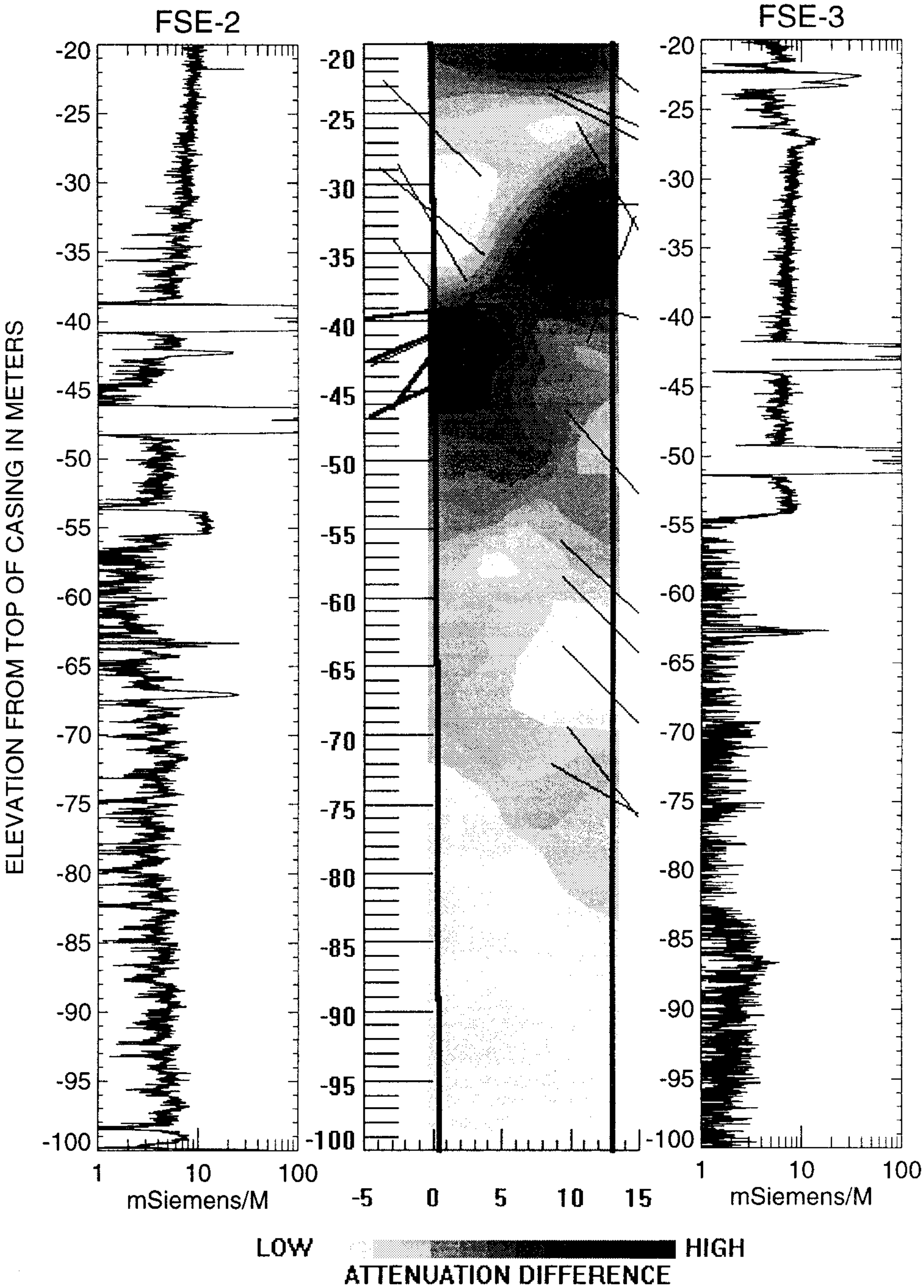

Figure 4. Gray scale attenuation difference tomogram with superimposed radar fracture trace interpretations flanked by induction logs for wells FSE-2 and FSE-3. The darker the gray in the tomogram, the larger the absolute value of the change in attenuation. The fracture trace orientations indicate the apparent dip of the fractures in the FSE2-3 plane. The lengths of the fracture traces are not significant, but four fracture traces adjacent to well FSE-2 are thicker to indicate that they are interpreted to be more hydraulically transmissive. The fracture traces were interpreted from data produced by the directional borehole radar (RAMAC system). The off-scale portions of the FSE-2 and FSE-3 induction logs are responses to the metal rings on the packers (see Figure 2). There is a narrow increase in conductivity in the FSE-2 log at -42.3 m that correlates both with one of the transmissive fractures and with the highest difference in the tomogram.

As another check on conditions in the wells we ran borehole fluid resistivity logs that are shown in Figure 5. These indicate order-of-magnitude higher resistivity below -55 m in FSE-3 than in FSE-2 and constant resistivities in both wells below that level. FSE-3 was run only once, after completion of the experiments, but FSE-2 was run before and after and shows what we interpret to be mixing due to tool motion in the well. The stratification at about -45 m is smoothed. The reason for the order-of-magnitude difference in resistivity below -50 m is residual brine from experiments in 1995. More brine entered FSE-2 than FSE-3 because of the more transmissive fractures that intersect FSE-2. Although we cannot completely rule out changes in borehole fluid resistivity during the experiment as a possible source of error, the locations of differences in attenuation in the tomogram in Figure 4 do not match the changes of borehole fluid resistivity seen in Figure 5.

EXPERIMENTAL SOURCES OF ERROR IN TOMOGRAPHY DATA SETS

Tomography data sets are never perfect. Possible errors can be of several types: (1) Positional errors due to cable slippage on a measurement wheel, cable stretch, miscalibration of the measuring wheel, or inaccurate well deviation data; (2) Time errors due to time base shifts in the radar system, errors in picking the first arrival, or errors in compensation for zero-time offset; (3) amplitude errors due to noise (primarily for low amplitude signals), lack of system amplitude stability, or lack of linearity (primarily for large signals) in the receiver. For difference measurements, one must add to this list (4) the possibility of changes in electrical properties during data acquisition. Tomographic algorithms assume that the electromagnetic properties of a given volume element are constant for all raypaths through that volume element for each particular suite of measurements. This dictates how data should be taken in difference experiments (Lane and others, 1998a). Of course to some degree all real data are noisy and therefore inconsistent, but it is desirable to minimize the inconsistencies to produce the best possible tomographic reconstruction. We conclude that the addition of the log-through packers to prevent major brine tracer incursions into the observation wells was justified despite the additional logistical complexity introduced.

CONCLUSIONS

The borehole radar and tomography conducted at Mirror Lake, Grafton County, New Hampshire in fractured crystalline rock using a brine tracer imaged fluid flow paths. Correlation of reflection radar and tomography is high and lends confidence that the results are accurate and that such studies can provide a useful tool for hydraulic flow and transport studies. Transient changes in electrical conductivity using a brine tracer in the fractured crystalline rock were observed and can be exploited to aid hydraulic modeling. We caution, however, that if the experiments are not carefully done, the transient behavior becomes an obstacle to accurate tomographic inversion.

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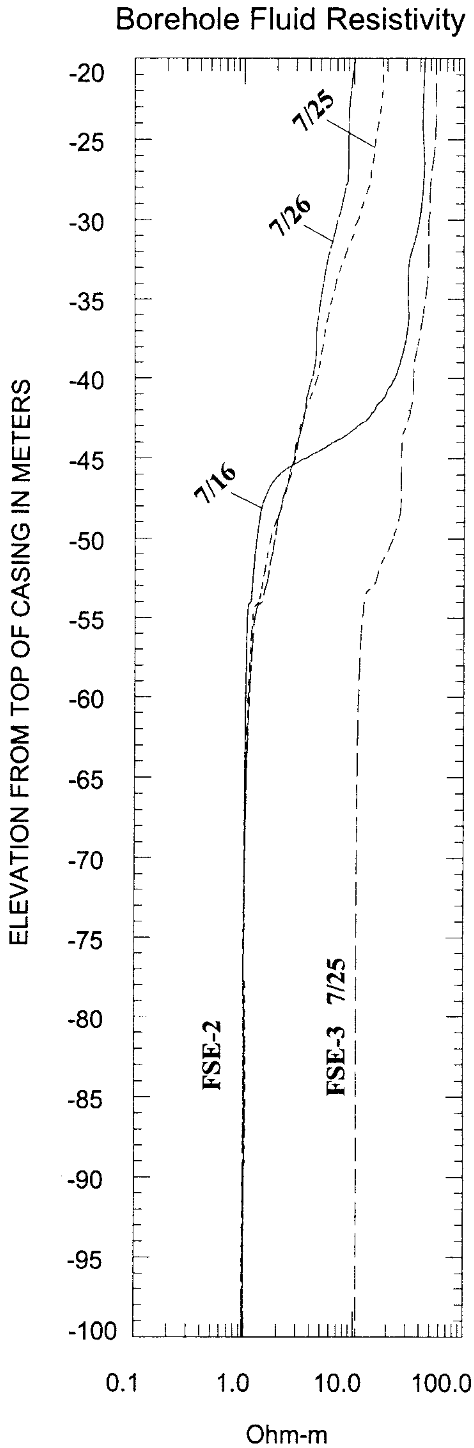

Figure 5. Borehole fluid resistivity for wells FSE-2 and FSE-3. Fluid resistivity logs in FSE-2 were run three times; on 7/16/97 before any radar logs and prior to the first brine injection of the season, on 7/25/96 after completion of the tomography and borehole radar, and on 7/26/97. The FSE-3 fluid resistivity log shown was run on 7/25/97. We speculate that the differences observed in the FSE-2 logs are due primarily to mixing caused by running borehole tools up and down the well.

REFERENCES

Day-Lewis, F.D., Lane, J.W.Jr., Haeni, F.P., and Gorelick, S.M., 1997, Combining borehole radar, saline tracer tests, and numerical modeling to identify flow paths in fractured rock. Proceedings of the American Geophysical Union, San Francisco, California, December, 1997.

Lane, J.W.Jr., 1996, Use of borehole radar methods to detect a saline tracer in fractured crystalline rock. Unpublished Master's Thesis, University of Connecticut, 165p.

Lane, J.W.Jr., Haeni, F.P., Placzek, G., Wright, D.L., 1996, Use of borehole radar methods to detect a saline tracer in fractured crystalline bedrock at Mirror Lake, Grafton County, New Hampshire: Proceedings, GPR '96, Sixth International Conference on Ground Penetrating Radar, Sendai, Japan, September 30- October 3, 1996, p.185-190.

Lane, J.W.,Jr., Joesten, P.K., Haeni, F.P., Vendl, M., and Yeskis, D., 1998a, Use of borehole-radar methods to monitor the movement of a saline tracer in carbonate rock at Belvidere, Illinois: Proceedings of the Symposium on the Application of Geophysics to Environmental and Engineering Problems (SAGEEP'98), Chicago, Illinois, March 22-26, 1998, (this Proceedings).

Lane, J.W.,Jr., Haeni, F.P., Versteeg, R., 1998b, Use of a multi-offset borehole-radar reflection method in fractured crystalline bedrock at Mirror Lake, Grafton County, New Hampshire: Proceedings of the Symposium on the Application of Geophysics to Environmental and Engineering Problems (SAGEEP'98), Chicago, Illinois, March 22-26, 1998, (this Proceedings).

Liu, L., Zhou, C., Lane, J.W.Jr, and Haeni, F.P., 1997, Cross-hole radar attenuation tomography using a frequency centroid downshift method: consideration of non-linear frequency dependence of EM wave attenuation. Proceedings of the Society of Exploration Geophysics International Exposition and Sixty-Seventh Annual Meeting, Dallas, Texas, November 2-7, 1997, p. 442-445.

Williams, J.H., 1994, Application of electromagnetic-induction logging to ground-water-quality studies *in* Paillet, F.L., and Williams, J.H., eds., Proceedings of the U.S. Geological Survey Workshop on the Application of Borehole Geophysics to Ground-Water Investigations, Albany, New York, June 2-4, 1992: Water-Resources Investigations Report 94-4103.

Wright, D.L., Grover, T.P., Ellefsen, K.J., Lane, J.W.Jr., and Kase, P.G., 1996, Radar tomograms at Mirror Lake, New Hampshire: 3-D visualization and a brine tracer experiment: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP'96), Keystone, Colorado, April 28-May 2, 1996, p. 565-575.